Emergence of the Green's Functions from Noise and Passive Acoustic Remote Sensing of Ocean Dynamics

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LONG-TERM GOALS

- To evaluate feasibility and determine physical limits of performance of a passive acoustic system for characterization of a time-varying ocean where ambient acoustic noise is utilized as a probing signal.
- To develop a passive remote sensing technique for acoustic characterization of oceanic currents.

OBJECTIVES

1. To demonstrate theoretically emergence of the deterministic Green's functions (GFs) from noise sources distributed in a volume and on boundaries in inhomogeneous, fluid-solid environments with dissipation.
2. To investigate a relation between the deterministic GFs and a two-point correlation function of noise in a low-frequency regime where stationary-point arguments become inapplicable.
3. To quantify degradation of performance of passive remote sensing techniques due to ocean surface motion and other variations of underwater sound propagation conditions in time.
4. To retrieve flow-induced non-reciprocity of acoustic phase and amplitude of the deterministic GFs from cross-correlation of diffuse sound fields generated as a result of scattering by inhomogeneities in the water column and/or by seafloor and sea surface roughness.
5. To determine accuracy of current velocity measurements using acoustic travel time non-reciprocity retrieved from a two-point noise cross-correlation.
6. To evaluate, for shallow- and deep-water scenarios, optimal parameters of a passive acoustic system for ocean temperature and current velocity measurements using cross-correlation of ambient noise and/or sound fields generated by sources of opportunity.

APPROACH

This work includes theoretical research and numerical simulations of ambient noise fields. Our theoretical approach is based on the flow reversal theorem(Godin, 1997), which is an extension of the reciprocity principle to moving media. The approach proved to be instrumental in deriving exact representations of the noise fields and their statistics in arbitrarily inhomogeneous, moving media in terms of deterministic GFs (Godin, 2006, 2007a). Moreover, the flow reversal theorem leads to important identities (often termed Ward identities), which relate surface integrals of certain products of

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14. ABSTRACT

To evaluate feasibility and determine physical limits of performance of a passive acoustic system for characterization of a time-varying ocean where ambient acoustic noise is utilized as a probing signal

15. SUBJECT TERMS

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GFs to the GF value at a point and underlie an exact, local relation between diffuse noise cross-correlations and deterministic GFs (Godin, 2006, 2007a).

Assessment of feasibility of passive acoustic remote sensing requires calculation of averages over finite time interval, rather than statistical ensemble averages. In addition, the fourth statistical moments of the random field as well as their estimates obtained with averaging over a finite time interval need to be calculated. Again, the integral representations of the noise field due to random sources distributed on a surface and/or in a volume, which are obtained from the flow reversal theorem, are the starting point of the analysis. Unlike the second statistical moments (Rytov, 1953; Godin, 2007a), closed-form, exact relations for the fourth moments and finite-time averages are unlikely to exist in generic inhomogeneous media. When applicable, asymptotic techniques (Snieder, 2004; Godin, 2006) are employed to evaluate the higher statistical moments and the finite-time averages. Specific features of the oceanic environment, such as slowness of the variation in the horizontal plane compared to variation with depth, are utilized in conjunction with the parabolic approximation and/or normal mode representation of the field to determine the information content of two-point cross-correlations of the ambient noise and of the multiply-scattered field from sources of opportunity. Quasi-stationary approximation (Godin, 2002) is used to quantify effects of the sea surface and the sound speed time-dependences on feasibility of inverting noise cross-correlations for parameters of the sound speed and, especially, current velocity fields.

The key individuals that have been involved in this work are Oleg A. Godin (CIRES/Univ. of Colorado and NOAA/ESRL), Nikolay A. Zabotin (CIRES/Univ. of Colorado), Anatoli L. Levchin (Physics Dept./Univ. of Colorado), and Benjamin D. Hamlington (CCAR/Univ. of Colorado). Dr. Zabotin focused on evaluating observation times necessary for GF retrieval from ambient noise in an underwater acoustic waveguide under conditions of adiabatic propagation. Mr. Hamlington performed numerical simulations of acoustic fields generated by random sources. Dr. Levchin contributed his expertise on the techniques, which were previously developed in the seismology community for deterministic GFs retrieval from diffuse wave fields. Dr. Godin took the lead in theoretical description of long-range correlations of random acoustic fields in inhomogeneous, moving media.

WORK COMPLETED

Using thermal acoustic noise as a physically consistent model of a diffuse noise field, it has been demonstrated theoretically that, with an appropriate choice of acoustic observables, time derivative of a two-point correlation function of noise is proportional to the sum of deterministic GFs, which correspond to sound propagation in opposite directions between the two points (Godin, 2008e). Unlike earlier theories, the result applies equally to open systems, waveguides, and resonators, fluid and fluid-solid systems with dissipation, and allows for arbitrary inhomogeneous background fluid motion (currents). For perfectly diffuse noise fields, such as thermal noise, the relation between deterministic GFs and the cross-correlation function of noise is exact and, in particular, remains valid in a low-frequency regime where stationary-point arguments become inapplicable (Godin, 2008e).

For further use in analyses of diffuse noise fields and their possible utilization in passive acoustic characterization of various aspects of the underwater environment, acoustic GFs have been studied for various scenarios of interest. In particular, it has been established that travel times of ray arrivals may remain stable and predictable when trajectories of individual rays are strongly distorted and unpredictable due to multiple scattering of the wave by sound-speed fluctuations, such as perturbations

induced by internal gravity waves (Godin, 2007b). New, more accurate far-field asymptotic expansions of GFs have been obtained for sound sources and/or receivers located near a fluid-fluid interface (Brekhovskikh and Godin, 2008). The asymptotic GFs have been applied to model sound radiation and scattering by objects located on or embedded in the ocean bottom (Zampolli *et al*., 2008). Peculiarities of low-frequency GFs associated with acoustic power leakage from underwater waveguide into atmosphere have been studied in some detail assuming plane (Godin, 2008b, c) or statistically rough (Fuks and Godin, 2008) air-water interface, including an interface sound wave supported by rough ocean surface. These results are summarized in a review paper (Godin, 2008d). For sound propagation between a point in deep water and a point in very shallow water or on shore, it has been shown that the acoustic GF features a distinct, strong component, which results from coupling between seismo-acoustic interface waves and acoustic normal modes (Godin, 2008a). Detection of the corresponding component in cross-correlation functions of ambient noise appears to be a promising technique for measuring attenuation of compressional and shear waves in marine sediments.

Theoretical methods of investigation of sound fields in range-dependent and horizontally inhomogeneous oceans with and without currents have been summarized in a book (Brekhovskikh and Godin, 2008). A book on historical development of underwater acoustics research and technology in Russia and the former Soviet Union has been published (Godin and Palmer, 2008).

RESULTS

When studying correlation properties of diffuse acoustic fields in fluid-solid systems with dissipation, we assumed the diffuse field to be of thermal origin. Unlike other types of noise, thermal noise represents chaotic thermal motion of molecules, atoms, ions, and electrons and is inevitably present in fluids and solids. It can be viewed as generated by delta-correlated random sources distributed throughout the volume. Thermal noise often dominates the noise field at sufficiently high frequencies.

The environment is supposed to be stationary (i. e., time-independent) and consist of an arbitrary inhomogeneous moving fluid and an arbitrary inhomogeneous, anisotropic solid. Absorption is modeled by attributing a frequency-dependent imaginary part to the fluid compressibility and the elastic modulus tensor of the solid.

At thermal equilibrium it was found that, in the frequency domain, the cross-correlation of thermal noise in acoustic pressure equals the product of a temperature-dependent function, which does not depend on coordinates, and a sum of the CW GFs which describe sound propagation in opposite directions between the two points (Godin, 2008e). The GF here is understood to be the acoustic pressure field generated by a point source of volume velocity. Similar results are obtained for thermal noise within solid. Thus, the cross-correlation function of thermal fluctuations of stresses within the solid is proportional to the sum of the deterministic Green's tensors that correspond to sources of external strain and describe wave propagation in opposite directions between the two points (Godin, 2008e). In the time domain, acoustic Green's functions and tensors corresponding to wave propagation in either direction between two given points are expressed as time derivatives of cross-correlation functions of thermal fluctuations of respective acoustic observables. Remarkably, the parameters specifying dissipative properties of the medium drop out from the final results.

The practical significance of our theoretical findings lies in their possible application to passive acoustic characterization of fluid-solid systems, including monitoring of the physical parameters of

inhomogeneous flows. In many geophysical, engineering, and biomedical applications, the flow velocity is small compared to the phase speed of elastic waves. For instance, the ratio of velocity of ocean currents to sound speed typically does not exceed $3 \cdot 10^{-4}$. Admissible absolute errors in flow velocity measurements are often much smaller than uncertainty in knowledge of the sound speed. The difficulties of remote sensing of slow flows in uncertain environments are overcome by measurements of acoustic non-reciprocity in reciprocal transmission experiments, where time-synchronized acoustic transceivers, i.e. a combination of a sound source and receiver(s), are employed to generate and receive signals propagating in opposite directions. Non-reciprocity of acoustic observables, such as the difference in travel times or phases of waves propagating between two points in opposite directions, is induced by fluid flow, vanishes in quiescent media, and is insensitive to uncertainties in sound speed and system geometry. Reciprocal transmission experiments enable active acoustic tomography of slow flows (Munk *et al.*, 1995). Our results demonstrate that all the information normally obtained via active reciprocal transmissions is retrievable from cross-correlation of thermal noise. Note that one can make noise measurements in a motionless part of the fluid or within the solid. Thus, ambient noise cross-correlation can be employed for passive acoustic characterization of inhomogeneous flows in fluid-solid environments. The key practical limitation of the approach is the requirement of a sufficiently long averaging time necessary to evaluate the correlation function of noise, during which the system needs to remain time-invariant.

IMPACT/APPLICATIONS

Passive acoustic techniques offer important advantages over ocean remote sensing with active techniques: low cost (a receiver substitutes a technologically much more complicated transceiver), possibility of noninvasive (in particular, avoiding any harm to marine life potentially associated with powerful underwater sound sources) and clandestine measurements in denied areas. Furthermore, the passive systems allow for exploitation of extremely broad bandwidth of ambient noise which exceeds by far the bandwidth of available non-explosive manmade sound sources used in remote sensing; much longer periods of autonomous operation due to drastic reduction of power consumption; and increased spatial resolution of measurements due to the greater number of paths along which the Green's function is evaluated, compared to an active system with the same number of sensors.

RELATED PROJECTS

None.

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HONORS/AWARDS/PRIZES

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